Micromechanical Membrane Switches for Microwave Applications

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Abstract

This paper proposes the fabrication of low-cost, low-loss microwave switches using thin metal membranes actuated by electrostatic fields. Measurement of switch test structures and modeling indicates that these devices have a potential 1,000- to 2,000-GHz figure-of-merit. Various aspects of fabrication, design, performance, and application of these devices are discussed.

Introduction

Over the past five years, developments in micromechanical technology have enabled the exciting development of an array of microminiature components such as motors, optical switches, spatial light modulators, high definition television displays, and accelerometers. To date, few efforts have been made to exploit this technology for microwave applications. In 1979, Petersen[1] described the use of micromechanical cantilever structures to perform switching of electrical signals at low frequencies. In 1991, Larson et al.[2] described the operation of rotary mechanical microwave switches. While these switches demonstrated excellent insertion performance up to 40 GHz, they had difficulty establishing proper contact between the rotor and the switch contacts, and required high voltages for actuation. The switches discussed in this paper are an offshoot of micromechanical membranes structures used to perform switching of optical signals on silicon substrates[3]. These switches use a thin metal membrane that is actuated by a DC potential to make or break the path of a microwave signal. By selecting the proper materials and dimensions for the membrane and electrodes, these switches can be used to switch microwave signals with reasonable switching voltages.

Switch Operation

The cross-sectional and top views of a simple single-pole single-throw membrane switch cell are depicted in Figures 1(a) and 1(b). This particular switch configuration consists of input and output transmission line contacts as well as a separate control line. The input signal traverses from a transmission line into a via interconnect that brings the signal to the top of the membrane. The output microwave line connects to a thin metal strip underneath the membrane. When a DC potential is applied to the control electrode, the attractive force caused by accumulated charges causes the membrane to pull downwards. With enough voltage, the membrane deforms until it comes in contact with the bottom microwave contact, closing the two poles of the switch as shown in Figure 1(c). This form of resistive switch has a low resistance path between the contacts in the on state, and a low capacitance between them in the off state. The control electrodes are recessed beneath the top plane of the IC to prevent shorting between the membrane and control electrodes. Small insulating posts are matrixed throughout the control electrode to keep the membrane from entering into the control electrode trench. When the DC potential on the control electrode is removed, the tensile forces of the stretched membrane pull it back into the up position. In this state, the parasitic fringing capacitance between the top membrane and the bottom contact determine the amount of isolation between the two switch poles.

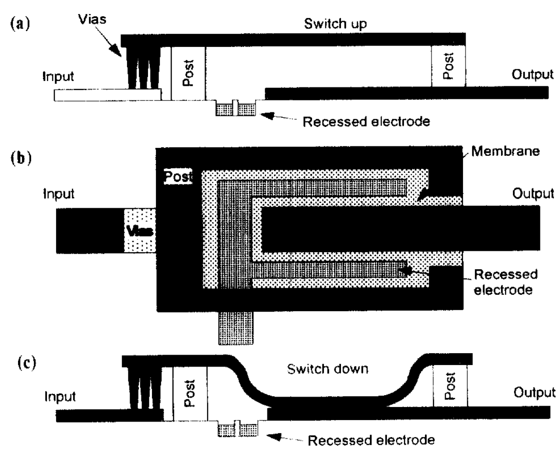

Figure 1. A Simple Single-Pole Single-Throw Membrane Switch

Membrane Processing

Several varieties of micromechanical membrane devices have been fabricated at Texas Instruments. Current microwave switch efforts leverage the fabrication of existing processes established for optical switches. The process flow is as follows: (1) an insulating layer of SiO_2 is thermally grown on the substrate, (2) the control electrode trench is lithographically defined and dry etched [Figure 2(a)], (3) a thin layer of aluminum is deposited, (4) this first metal layer is patterned and etched to define both top and recessed metallization [Figure 2(b)], (5) a polymer spacer layer is deposited, (6) the spacer layer is patterned and etched [Figure 2(c)], (7) metallization is deposited and etched to define the top metal membrane and vias [Figure 2(d]), and finally (8) the unwanted spacer under the membrane is removed with a dry etch undercut [Figure 2(e)].

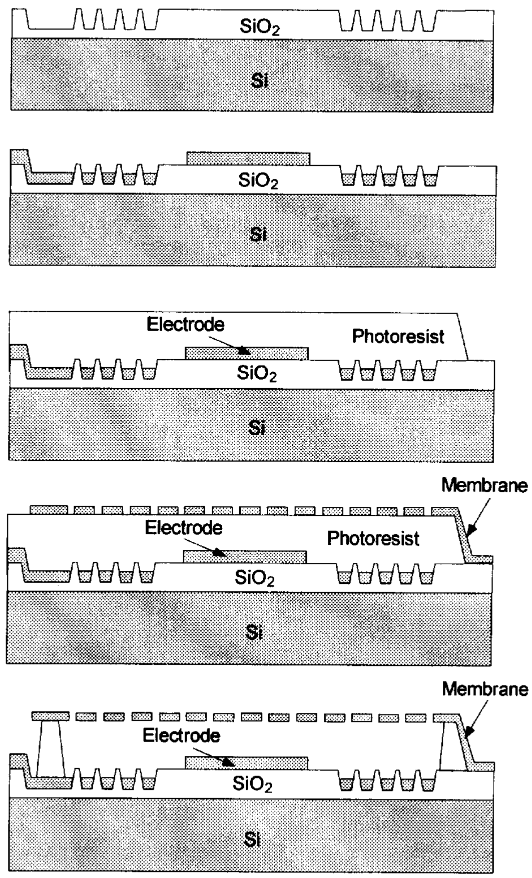

Figure 2. Membrane Processing Flow

This particular process scheme is relatively straightforward and compatible with low-cost processing. As such, this process is relatively compatible with silicon CMOS processing with costs on the order of cents/square millimeter. Since the silicon substrate only provides a medium for the transmission lines and mechanical support, other microwave materials such as alumina or sapphire could be used. However, the use of intrinsic silicon with aluminum makes this microwave switch compatible with CMOS processing. This would allow the integration of smart CMOS control circuitry to provide logic decoding and level shifting necessary to drive the microwave switches.

Experimental Results and Modeling

Figure 3 shows a photograph of a experimental switch that was fabricated at Texas Instruments. This particular device was fabricated within a process run of optical switches and consequently was built on doped silicon. This negates the possibility of making meaningful microwave measurements, but does allow measurement and observation of the device's low-frequency switching characteristics and mechanical properties.

The switch shown in Figure 3 has the dimension of 700 x 830 x 625 μm. The chip incorporates 0.4-μm-thick aluminum metal electrodes and a membrane fabricated on 3.5 μm of SiO_2 on top of doped silicon. The membrane posts support the metal membrane 2.0 μm above the top of the SiO_2 layer. The control lines are recessed 1.5 μm deep into the oxide.

Membrane actuation was tested by putting the top membrane at DC ground potential and applying a voltage on the control electrodes. At approximately 30 to 50 volts, the metal membrane snaps down. This is consistent with theoretical calculations of 45.4 volts for a 250 x 250-μm membrane.

To estimate the switch performance at microwave frequencies, measurements were made of the low-frequency on resistance and off capacitance. Measurements of resistance between the two switch contacts yielded 1.5 to 2.5 Ω of DC resistance. This resistance is determined by the area of the metal contact, the resistivities of the metal, and the degree to which the two metals come in contact. The off isolation performance of the switch was measured with an HP4275A LCR meter and kelvin probes at 10 MHz. The off capacitance is approximately 35 fF. This compares well with transmission line calculations of 29.5 fF for the line capacitance and end effect between the bottom contact and the membrane. These measurements indicate a figure of merit $f = 1/(2\pi R_{on}C_{off})$ of approximately 2,000 GHz. This compares well with typical figures of merit around 300 to 400 GHz for GaAs switching FETs and 1,500 to 2,000 GHz for GaAs p-i-n diodes.

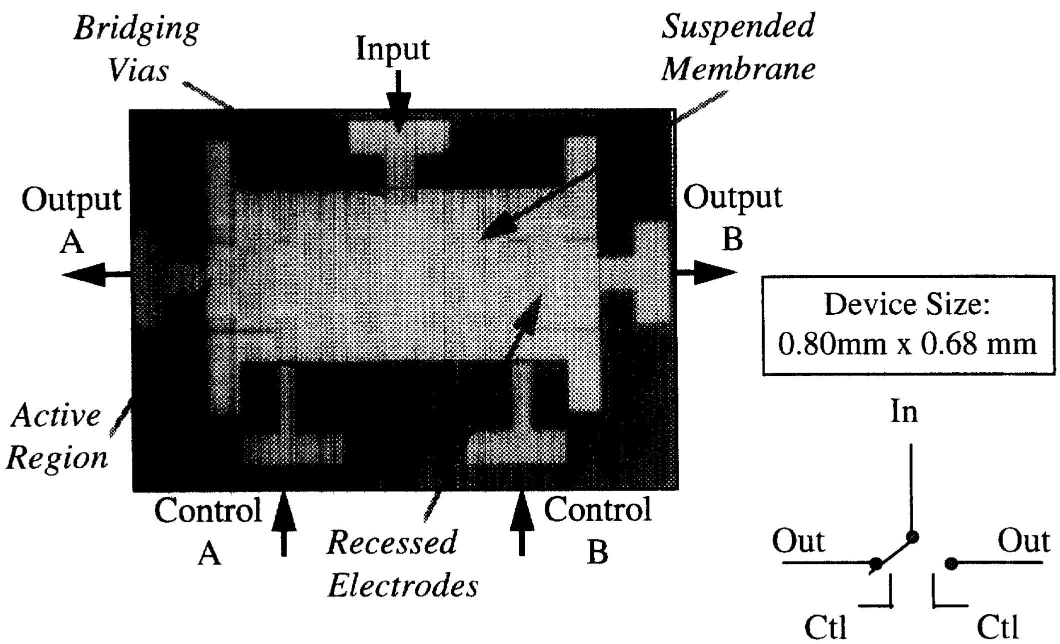

Figure 3. Experimental Switch

A distinct limitation of micromechanical switches is that they are inherently slower than semiconductor devices. Measurements on similarly processed membranes (for optical switching) indicates turnon and turnoff times on the order of tens to hundreds of microseconds, depending on the particular size of the membrane and the geometry of its support structures.

Applications

The compatibility of membrane switch construction with silicon CMOS processing makes this RF switch an attractive candidate for microwave integration with other passive RF devices. Low cost microwave phase shifters can be fabricated using this technology and incorporated on the same substrate with other active or passive components.

Figure 4(a) shows a schematic of a 4-bit time delay phase shifter in which various transmission line lengths are interconnected using RF switches. Any differential phase value from 0 to 360 degrees can be achieved in 22.5-degree increments by appropriate settings of the eight switch positions. A microwave network model of the 4-bit phase shifter using membrane switch parameters was constructed. The theoretical insertion loss from 8 to 12 GHz for all 16 possible phase shifter phase states is shown in Figure 4(b). Silicon substrate loss properties and calculated switch capacitances were used in the analysis with 1.5-dB insertion loss maximum predicted at 12 GHz.

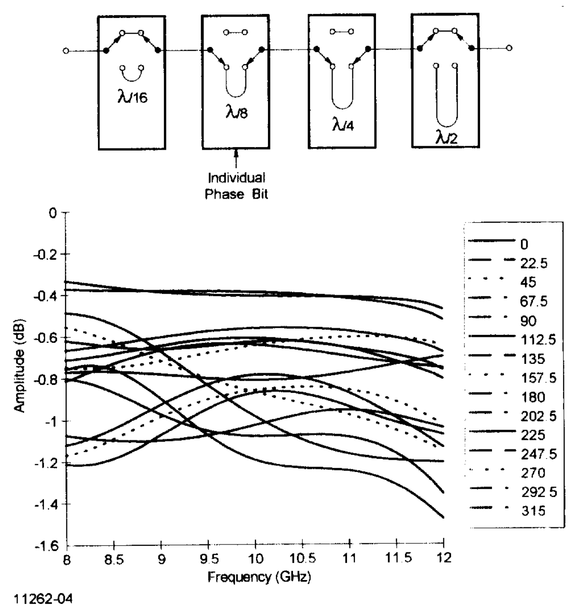

Figure 4. 4-Bit Time Delay Phase Shifter

Figure 5 shows a preliminary layout of a 4 x 4 subarray module utilizing the membrane switch time delay phase shifters. Square patch radiators excited by probe fed transmission lines attach to the various 4-bit phase shifters

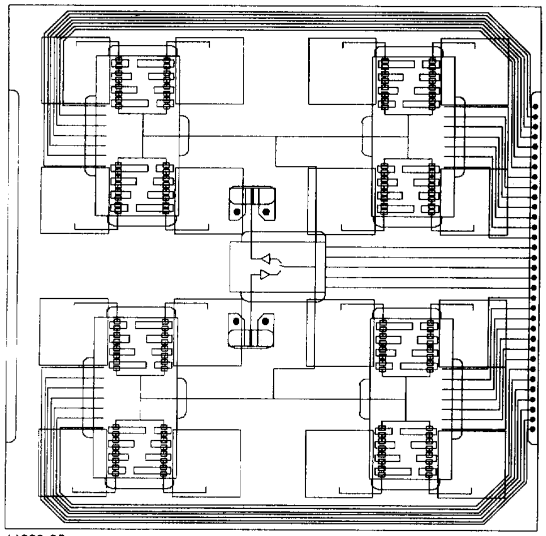

Figure 5. Layout of 4 × 4 Subarray Module Utilizing Membrane Switch Time Delay Phase Shifters

constructed on silicon substrate. A corporate feed manifold network collects the 16 phase shifters and radiators and is connected to either the power amplifier (PA) for transmit or the low-noise amplifier (LNA) for receive. The integration properties of the membrane switch with other devices make this 4 x 4 subarray packaging very compact and attractive as a basic building block for a large low cost phased array.

Conclusions

We have shown that micromechanical membrane switches possess the potential for low-cost, low-loss switches for microwave applications. These devices, with figures of merit on the same order as p-i-n diodes, offer the potential for switches that are compatible with silicon processing and orders of magnitude lower in cost than current GaAs technology. Additionally, the prospect of integration of these devices into existing passive circuitry on ceramic or glass substrates can make for very low loss interconnects with low parasitics. The large number of degrees of freedom and flexibility for choosing the materials, dimensions, and layouts for these switches offers exciting possibilities for much further improvements in performance and cost.

Acknowledgements

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